MATTERS OF GRAVITY

The newsletter of the Topical Group on Gravitation of the American Physical Society

Number 38 **Fall 2011**

Contents

Editor

David Garfinkle

Department of Physics Oakland University Rochester, MI 48309
Phone: (248) 370-3411
Internet: `garfinkl-at-oakland.edu`
WWW: `http://www.oakland.edu/?id=10223&sid=249#garfinkle`

Associate Editor

Greg Comer

Department of Physics and Center for Fluids at All Scales,
St. Louis University, St. Louis, MO 63103
Phone: (314) 977-8432
Internet: `comergl-at-slu.edu`
WWW: `http://www.slu.edu/colleges/AS/physics/profs/comer.html`

ISSN: 1527-3431

Editorial

The next newsletter is due February 1st. This and all subsequent issues will be available on the web at `https://files.oakland.edu/users/garfinkl/web/mog/` All issues before number **28** are available at `http://www.phys.lsu.edu/mog`

Any ideas for topics that should be covered by the newsletter, should be emailed to me, or Greg Comer, or the relevant correspondent. Any comments/questions/complaints about the newsletter should be emailed to me.

A hardcopy of the newsletter is distributed free of charge to the members of the APS Topical Group on Gravitation upon request (the default distribution form is via the web) to the secretary of the Topical Group. It is considered a lack of etiquette to ask me to mail you hard copies of the newsletter unless you have exhausted all your resources to get your copy otherwise.

David Garfinkle

Correspondents of Matters of Gravity

- John Friedman and Kip Thorne: Relativistic Astrophysics,
- Bei-Lok Hu: Quantum Cosmology and Related Topics
- Veronika Hubeny: String Theory
- Beverly Berger: News from NSF
- Luis Lehner: Numerical Relativity
- Jim Isenberg: Mathematical Relativity
- Katherine Freese: Cosmology
- Lee Smolin: Quantum Gravity
- Cliff Will: Confrontation of Theory with Experiment
- Peter Bender: Space Experiments
- Jens Gundlach: Laboratory Experiments
- Warren Johnson: Resonant Mass Gravitational Wave Detectors
- David Shoemaker: LIGO Project
- Stan Whitcomb: Gravitational Wave detection
- Peter Saulson and Jorge Pullin: former editors, correspondents at large.

Topical Group in Gravitation (GGR) Authorities

Chair: Patrick Brady; Chair-Elect: Manuela Campanelli; Vice-Chair: Daniel Holz. Secretary-Treasurer: James Isenberg; Past Chair: Steve Detweiler; Members-at-large: Scott Hughes, Bernard Whiting, Laura Cadonati, Luis Lehner, Michael Landry, Nicolas Yunes.

New developments in space-based gravitational wave astronomy

Karsten Danzmann, Max Planck Institute for Gravitational Physics
Karsten.Danzmann-at-aei.mpg.de

For almost two decades now, ESA and NASA have studied the LISA mission for the observation of low-frequency gravitational waves as an equally shared partnership of the two agencies.

ESA has recently changed the guidelines for large ("L-class") missions in the Cosmic Vision framework to require European-only funding, because NASA was financially unable to proceed on the timescale of the launch of the first L-class mission ('L1') in ESAs Cosmic Vision Programme:

`http://sci.esa.int/science-e/www/area/index.cfm?fareaid=100`

A search for a European-led variant of LISA that could be launched by 2022 was begun.

After studying several configurations, a new baseline for transfer, orbit and layout has been identified that will be refined in the coming month with the help of European industry. The new baseline employs less costly orbits, and simplifies the design of LISA by reducing the distance between the satellites and employing four rather than six laser links. This considerably reduces the mass and cost, while retaining much of the original science, in part because of new approaches to data analysis.

The European Science Team and a Science Task Force, composed of members of the gravitational wave and astrophysics communities in both Europe and the US, have assessed the scientific validity of the new LISA baseline for the fields of physics, astrophysics and cosmology and have shown that the new configuration should detect thousands of galactic binaries, tens of (super)massive black hole mergers out to a redshift of z=10 and tens of extreme mass ratio inspirals out to a redshift of 1.5 during its two year mission. The investigation of fundamental physics and cosmology tests will continue over the next few months, until we have a finalized mission proposal by the fall of 2011. The preliminary results of this investigation are looking promising.

This announcement is not an official statement of ESA or NASA.

we hear that ...

David Garfinkle, Oakland University garfinkl-at-oakland.edu

Daniel Holz was elected Vice Chair of GGR; Jim Isenberg was elected Secretary/Treasurer of GGR; and Michael Landry and Nicolas Yunes were elected Members at large of the Executive Committee of GGR.

Hearty Congratulations!

Finally, Results from Gravity Probe B

Clifford M. Will, Washington University, St. Louis[1] cmw-at-wuphys.wustl.edu

The great blues singer Etta James' signature song begins, "At laaasst, my love has come along ..." This may have been the feeling on May 4, 2011 when NASA announced the long-awaited results of Gravity Probe B [1], which appeared in Physical Review Letters [2]. Over 47 years and 750 million dollars in the making, Gravity Probe B was an orbiting physics experiment, designed to test two fundamental predictions of Einsteins general relativity.

According to Einstein's theory, space and time are not the immutable, rigid structures of Newton's universe, but are united as spacetime, and together they are malleable, almost rubbery. A massive body warps spacetime, the way a bowling ball warps the surface of a trampoline. A rotating body drags spacetime a tiny bit around with it, the way a mixer blade drags a thick batter around.

The spinning Earth does both of these things, and this is what the four gyroscopes aboard the Earth-orbiting satellite Gravity Probe B measured. The satellite follows a polar orbit with an altitude of 640 kilometers above the Earth's surface. The warping of spacetime exerts a torque on the gyroscope so that its axis slowly precesses – by about 6.6 arcseconds (or 1.8 thousandths of a degree) per year – in the plane of the satellite's orbit. (To picture this precession, or "geodetic effect," imagine a stick moving parallel to its length on a closed path along the curved surface of the Earth, returning to its origin pointing in a slightly different direction than when it started.) The rotation of the Earth also exerts a "frame-dragging" effect on the gyro. In this case, the precession is perpendicular to the orbital plane and advances by 40 milliarcseconds per year. Josef Lense and Hans Thirring first pointed out the existence of the frame-dragging phenomenon in 1918, but it was not until the 1960s that George Pugh in the Defense Department and Leonard Schiff at Stanford independently pursued the idea of measuring it with gyroscopes.

There were four gyroscopes aboard Gravity Probe B (GP-B in NASA parlance). Each gyroscope is a fused silica rotor, about the size of a ping-pong ball, machined to be spherical and homogeneous to tolerances better than a part per million, and coated with a thin film of niobium. The gyroscope assembly, which sat in a dewar of 2440 liters of superfluid helium, was held at 1.8 degrees Kelvin. At this temperature, niobium is a superconductor, and the supercurrents in the niobium of each spinning rotor produce a "London magnetic moment" parallel to its spin axis. Extremely sensitive magnetometers (superconducting quantum interference detectors, or "SQUIDs") attached to the gyroscope housing are capable of detecting even minute changes in the orientation of the gyros' magnetic moments and hence the precession in their rotation predicted by general relativity.

At the start of the mission, the four gyros were aligned to spin along the symmetry axis of the spacecraft. This was also the optical axis of a telescope directly mounted on the end of the structure housing the rotors. Spacecraft thrusters oriented the telescope to point precisely toward the star IM Pegasi (HR 8703) in our galaxy (except when the Earth intervened, once per orbit). In order to average out numerous unwanted torques on the gyros, the spacecraft rotated about its axis once every 78 seconds.

GP-B started in late 1963 when NASA funded the initial R&D work that identified the new technologies needed to make such a difficult measurement possible. Francis Everitt became

[1]This is an extended version of a "Viewpoint" article, published by the American Physical Society in *Physics* **4**, 43 (2011), available at http://physics.aps.org/articles/v4/43. Published by permission of the APS.

	Measured	Predicted
Geodetic Precession (mas)	6602 ± 18	6606
Frame-dragging (mas)	37.2 ± 7.2	39.2

Table 1: Final results of Gravity Probe B

Principal Investigator of GP-B in 1981, and the project moved to the mission design phase in 1984. Following a major review of the program by a National Academy of Sciences committee in 1994, GP-B was approved for flight development, and began to collaborate with Lockheed-Martin and Marshall Space Flight Center. The satellite launched on April 20, 2004 for a planned 16-month mission, but another five years of data analysis were needed to tease out the effects of relativity from a background of other disturbances of the gyros.

Almost every aspect of the spacecraft, its subsystems, and the science instrumentation performed extremely well, some far better than expected. Still, the success of such a complex and delicate experiment boils down to figuring out the sources of error. In particular, having an accurate calibration of the electronic readout from the SQUID magnetometers with respect to the tilt of the gyros was essential. The plan for calibrating the SQUIDs was to exploit the aberration of starlight, which causes a precisely calculable misalignment between the rotors and the telescope as the latter shifts its pointing toward the guide star by up to 20 arcseconds to compensate for the orbital motion of the spacecraft and the Earth. However, three important, but unexpected, phenomena were discovered during the experiment that affected the accuracy of the results.

First, because each rotor is not exactly spherical, its principal axis rotates around its spin axis with a period of several hours, with a fixed angle between the two axes. This is the familiar "polhode" period of a spinning top. In fact this polhoding was essential in the calibration process because it led to modulations of the SQUID output via the residual trapped magnetic flux on each rotor (about 1 percent of the London moment). But the polhode period and angle of each rotor actually decreased monotonically with time, implying the presence of some damping mechanism, and this significantly complicated the calibration analysis. In addition, each rotor was found to make occasional, seemingly random "jumps" in its orientation – some as large as 100 milliarcseconds. Some rotors displayed more frequent jumps than others. Without being able to continuously monitor the rotors' orientation, Everitt and his team couldn't fully exploit the calibrating effect of the stellar aberration in their analysis. Finally, during a planned 40-day, end-of-mission calibration phase, the team discovered that when the spacecraft was deliberately pointed away from the guide star by a large angle, the misalignment induced much larger torques on the rotors than expected. From this, they inferred that even the very small misalignments that occurred during the science phase of the mission induced torques that were probably several hundred times larger than the designers had estimated.

What ensued during the data analysis phase was worthy of a detective novel. The critical clue came from the calibration tests. Here, they took advantage of the residual trapped magnetic flux on the gyroscope. (The designers used superconducting lead shielding to suppress stray fields before they cooled the niobium coated gyroscopes, but no shielding is ever perfect.) This flux adds a periodic modulation to the SQUID output, which the team used to figure

out the phase and polhode angle of each rotor throughout the mission. This helped them to figure out that interactions between random patches of electrostatic potential fixed to the surface of each rotor, and similar patches on the inner surface of its spherical housing, were causing the extraneous torques. In principle, the rolling spacecraft should have suppressed these effects, but they were larger than expected.

Fortunately, the patches are fixed on the various surfaces, and so it was possible to build a parametrized model of the patches on both surfaces using multipole expansions, and to calculate the torques induced by those interactions when the spin and spacecraft axes are misaligned, as a function of the parameters. One prediction of the model is that the induced torque should be perpendicular to the plane formed by the two axes, and this was clearly seen in the data. Another prediction is that, when the slowing decreasing polhode period crosses an integer multiple of the spacecraft roll period, the torques fail to average over the roll period, whereupon the spin axis precesses about its initial direction in an opening Cornu spiral, then migrates to a new direction along a closing Cornu spiral. This is known as a loxodromic path, familiar to navigators as a path of fixed bearing on the Earth's surface. Detailed observation of the orientation of the rotors during such "resonant jumps" showed just such loxodromic behavior. In the end, every jump of every rotor could be identified by its "mode number", the integer relating its polhode period to the spacecraft roll period.

The original goal of GP-B was to measure the frame-dragging precession with an accuracy of 1%, but the problems discovered over the course of the mission dashed the initial optimism that this was possible. Although Everitt and his team were able to model the effects of the patches, they had to pay the price of the increase in error that comes from using a model with so many parameters. The experiment uncertainty quoted in the final result – roughly 20% for frame dragging – is almost totally dominated by those errors. Nevertheless, after the model was applied to each rotor, all four gyros showed consistent relativistic precessions. Gyro 2 was particularly "unlucky" – it had the largest uncertainties because it suffered the most resonant jumps. Numerous cross-checks were carried out, including estimating the relativity effect during different segments of the 12-month science phase (various events, including computer reboots and a massive solar storm in January 2005, caused brief interruptions in data taking), increasing and decreasing the number of parameters in the torque model, and so on.

When GP-B was first conceived in the early 1960s, tests of general relativity were few and far between, and most were of limited precision. But during the ensuing decades, researchers made enormous progress in experimental gravity, performing tests of the theory by studying the solar system and binary pulsars [3]. Already by the middle 1970s, some argued that the so-called parametrized post-Newtonian (PPN) parameters that characterize metric theories of gravity, like general relativity, were already known to better accuracy than GP-B could ever achieve [4]. Given its projected high cost, critics argued for the cancellation of the GP-B mission. The counter-argument was that all such assertions involved theoretical assumptions about the class of theories encompassed by the PPN approach, and that all existing bounds on the post-Newtonian parameters involved phenomena entirely different from the precession of a gyroscope. All these issues were debated, for example, in the 1994 NAS/NRC review of GP-B that recommended its continuation.

The most serious competition for the results from GP-B comes from the LAGEOS experiment, in which laser ranging accurately tracked the paths of two laser geodynamics satellites orbiting the Earth. Relativistic frame dragging was expected to induce a small precession (around 30 milliarcseconds per year) of the orbital plane of each satellite in the direction of the Earth's rotation. However, the competing Newtonian effect of the Earth's nonspherical

shape had to be subtracted to very high precision using a model of the Earth's gravity field. The first published result from LAGEOS in 1998 [5, 6] quoted an error for the frame-dragging measurement of 20 to 30%, though this result was likely too optimistic given the quality of the gravity models available at the time. Later, the GRACE geodesy mission offered dramatically improved Earth gravity models, and the analysis of the LAGEOS satellites finally yielded tests at a quoted level of approximately 10% [7].

Frame dragging has implications beyond the solar system. The incredible outpouring of energy from quasars along narrow jets of matter that stream at nearly the speed of light is most likely driven by the same frame-dragging phenomenon measured by GP-B and LAGEOS. In the case of quasars, the central body is a rapidly rotating black hole. In another example, the final inward spiral and merger of two spinning black holes involve truly wild gyrations of each body's spin axes and of the orbit, again driven by the same frame-dragging effect, and these motions are encoded in gravitational-wave signals. Laser interferometric observatories on the ground, and in the future, a similar observatory in space, may detect these gravity waves. So there is a strong link between the physics Gravity Probe B was designed to uncover and that describing some of the most energetic and cataclysmic events in the universe.

Even though it is popular lore that Einstein was right (I even wrote a book on the subject), no such book is ever completely closed in science. As we have seen with the 1998 discovery that the universe is accelerating, measuring an effect contrary to established dogma can open the door to a whole new world of understanding, as well as of mystery. The precession of a gyroscope in the gravitation field of a rotating body had never been measured before GP-B. While the results support Einstein, this didn't have to be the case. Physicists will never cease testing their basic theories, out of curiosity that new physics could exist beyond the "accepted" picture.

Disclosure: CMW chaired NASA's external Science Advisory Committee for Gravity Probe-B from 1998 to 2011.

References

[1] Press conference available at `http://www.youtube.com/watch?v=SBiY0Fn1ze4`

[2] C. W. F. Everitt et al., Phys. Rev. Lett. 106, 221101 (2011).

[3] C. M. Will, Was Einstein Right? (Basic Books, Perseus, NY, 1993).

[4] C. M. Will, Living Rev. Relativ. 9, 3 (2006); `http://www.livingreviews.org/lrr-2006-3`

[5] I. Ciufolini et al., Class. Quantum Gravit. 14, 2701 (1997).

[6] I. Ciufolini et al., Science 279, 2100 (1998).

[7] I. Ciufolini et al., in *General Relativity and John Archibald Wheeler*, edited by I. Ciufolini and R. A. Matzner (Springer, Dordrecht, 2010), p. 371.

Discovery and EOS implications of the highest-mass ($2\,M_{\rm Sun}$) neutron star

Wynn C.G. Ho, University of Southampton wynnho-at-soton.ac.uk

In October 2010, radio astronomers announced the mass measurement of the neutron star known as PSR J1614−2230 [Demorest et al.(2010)]. The neutron star mass $M = 1.97 \pm 0.04\,M_{\rm Sun}$ is the most-accurate, high-mass neutron star known to date. PSR J1614−2230 is a radio pulsar with a 3.15 ms spin period and is in a 8.7 d binary orbit with a $M_{\rm c} = 0.5\,M_{\rm Sun}$ companion star. What contributed to making the mass measurement possible is that the binary system is viewed nearly edge-on, with an orbital inclination angle $i = 89^\circ.17 \pm 0^\circ.02$. The edge-on view allows a measurement of Shapiro delay and, combined with the large companion mass and excellent timing precision of a new instrument on the National Radio Astronomy Observatory Green Bank Telescope, yields a very accurate measurement of the mass of a neutron star.

Shapiro delay is a delay in the measured arrival times of light pulses from the neutron star due to this light passing through the gravitational potential of the companion star [Shapiro(1964)]. For nearly circular orbits, Shapiro delay is $\Delta_{\rm S} \approx -2r\ln(1 - s\sin\Phi)$, where Φ is the orbital phase and r and s are the Shapiro delay range and shape parameters, respectively, and are given by $r = GM_{\rm c}/c^3 = 4.9\,\mu{\rm s}\,(M_{\rm c}/M_{\rm Sun})$ and $s = \sin i$ [Damour & Taylor(1992), Lorimer & Kramer(2005)]. When the effect of Shapiro delay is strong, timing residuals from the pulsar signal show a characteristic peak at orbital phase $\Phi = 90^\circ$, which corresponds to superior conjunction or when the pulsar is behind companion star. Other measurements, e.g., gravitational redshift, orbital decay due to gravitational radiation, and orbital precession, allow degeneracies in the Shapiro delay equation to be broken and the mass to be determined uniquely and accurately. See [Kramer et al.(2006)] for a demonstration of this technique as applied to the double pulsar system PSR J0737−3039A/B, which yields the very accurate (uncertainty in last digit given in parentheses) neutron star masses $1.3381(7)\,M_{\rm Sun}$ and $1.2489(7)\,M_{\rm Sun}$. Note that PSR J0737−3039A/B has an inclination angle of $88^\circ.69^{+0^\circ.50}_{-0^\circ.76}$, so is viewed (marginally) less edge-on than PSR J1614−2230. Note also that the 3.15 ms spin period of PSR J1614−2230 is too slow to pose interesting constraints.

One of the reasons for studying neutron stars is to use them as probes of fundamental physics in regimes that cannot be accessed in laboratories on Earth. An important example is the nuclear equation of state (EOS). So what is the nuclear EOS, and how does measuring the mass of a neutron star constrain the EOS? I summarize arguments made in [Lattimer & Prakash(2010)]; see for details. The nuclear EOS determines the behavior of matter near nuclear densities (at $n_{\rm nuc} \approx 0.16$ fm^{-3} or $\rho_{\rm nuc} \approx 2.8 \times 10^{14}$ g cm^{-3}) and provides a relationship between pressure and density, i.e., $P(\rho)$. While the EOS is fairly well-known at $\rho \ll \rho_{\rm nuc}$, large uncertainties exist at $\rho \gtrsim \rho_{\rm nuc}$, and there are many detailed theoretical calculations of what it might be (see, e.g., [Lattimer & Prakash(2001), Lattimer & Prakash(2007)], and references therein). The EOS also determines the abundances of particles that comprise a neutron star; in the core near nuclear densities, the star is composed of neutrons, protons, electrons, and a small amount of muons. If the deep central regions of the neutron star can sustain high enough densities, a lower energy ground state may be achieved by the formation of particles beyond the typical constituents, exotic particles such as kaons, hyperons, or deconfined (up, down, and strange) quarks (see, e.g., [Lattimer & Prakash(2004)], for review).

How does the EOS affect neutron star mass (and radius)? In order to build a model of the structure of a cold, spherical (relativistic) star, one solves the Tolman-Oppenheimer-Volkoff (TOV) equations ([Tolman(1939), Oppenheimer & Volkoff(1939)]; see also [Shapiro & Teukolsky(1983)]): these equations describe hydrostatic equilibrium, mass conservation, and gravitational acceleration and are first-order differential equations for pressure P, enclosed mass m, and gravitational potential Φ as a function of radial distance r. An EOS $P(\rho)$ is needed to close this set of equations. The inner boundary condition, central density $\rho_{\rm c}$ [$\equiv \rho(r=0)$, which also prescribes the central pressure $P_{\rm c}$ via the EOS], is chosen. The TOV equations are then integrated outward until $P=0$, and this defines the total mass M and radius R of the star, i.e., $R \equiv r(P=0)$ and $M \equiv m(R)$. For a given theoretical $P(\rho)$, a M-R sequence can be constructed. The maximum mass $M_{\rm max}$ neutron star in the sequence is built using the maximum allowed central density $\rho_{\rm c,max}$ for that EOS. A star that is more massive than $M_{\rm max}$ would form a black hole. Note that General Relativity and causality (sound speed everywhere in the star is less than the speed of light; [Rhoades & Ruffini(1974), Lindblom(1984), Lattimer & Prakash(2004)]) provide constraints on M/R, i.e., $2GM < c^2R$ and $3GM < c^2R$, respectively. Normal matter EOSs yield stable configurations whose radius decreases with increasing mass, while quark EOSs produce "quark" or "strange" stars [Witten(1984), Farhi & Jaffe(1984)] whose radius increases with increasing mass. EOSs that are "stiff/soft" are ones which produce higher/lower $M_{\rm max}$ for a given R, and EOSs that involve exotic particles are generally soft EOSs with lower $M_{\rm max}$.

This last point highlights why it is important to measure the maximum mass of neutron stars. If the measured $M_{\rm max}$ is higher than the maximum mass allowed by a given theoretical EOS, then that EOS is ruled out. Taking $2\,M_{\rm Sun}$ to be the lower limit of the maximum mass, i.e., $M_{\rm max} \geq 2\,M_{\rm Sun}$, does this rule out any interesting EOSs? Unfortunately, the answer is no. Neutron star models containing, e.g., kaons, have been constructed with $M_{\rm max} \sim 2\,M_{\rm Sun}$ (see [Lattimer & Prakash(2010)], and references therein). For quark stars, [Witten(1984)] showed that $M_{\rm max} = 2.5\,M_{\rm Sun}$ is the absolute limit; more realistic quark star models have lower values of $M_{\rm max}$, but these can be above $2\,M_{\rm Sun}$. A reliable elimination of soft EOSs, such as those that produce strange quark stars, would be possible with a measurement of a $2.4\,M_{\rm Sun}$ neutron star (intriguingly the black widow pulsar, PSR B1957+20, has $M = 2.4\,M_{\rm Sun}$ though with rather large uncertainty [Reynolds et al.(2007), van Kerkwijk et al.(2011)van Kerkwijk, Breton, &x Kulkarni]). Nevertheless, the measured (highest) neutron star mass does constrain $\rho_{\rm c,max}$, which is given by $\rho_{\rm c,max} \approx 1.4 \times 10^{16}$ g cm$^{-3}(M_{\rm Sun}/M_{\rm max})^2$, for all EOSs [Lattimer & Prakash(2010)]. With $M = 2\,M_{\rm Sun}$ for PSR J1614−2230, the central density for any neutron star must be less than 3.5×10^{15} g cm^{-3}.

References

[Demorest et al.(2010)] P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts, and J. W. T. Hessels, Nature, 467, 1081 (2010)

[Shapiro(1964)] I. I. Shapiro, Phys. Rev. Lett., 13, 789 (1964)

[Damour & Taylor(1992)] T. Damour and J. H. Taylor, Phys. Rev. D, 45, 1840 (1992)

[Lorimer & Kramer(2005)] D. Lorimer and M. Kramer, Handbook of Pulsar Astronomy (Cambridge University Press, Cambridge, 2005)

[Kramer et al.(2006)] M. Kramer, et al., Science, 314, 97 (2006)

[Lattimer & Prakash(2010)] J. M. Lattimer and M. Prakash, arXiv:1012.3208

[Lattimer & Prakash(2001)] J. M. Lattimer and M. Prakash, Astrophys. J., 550, 426 (2001)

[Lattimer & Prakash(2007)] J. M. Lattimer and M. Prakash, Phys. Rep., 442, 109 (2007)

[Lattimer & Prakash(2004)] J. M. Lattimer and M. Prakash, Science, 304, 536 (2004)

[Tolman(1939)] R. C. Tolman, Phys. Rev., 55, 364 (1939)

[Oppenheimer & Volkoff(1939)] J. R. Oppenheimer and G. M. Volkoff, Phys. Rev., 55, 374 (1939)

[Shapiro & Teukolsky(1983)] S. L. Shapiro and S. A. Teukolsky, Black Holes, White Dwarfs, and Neutron Stars (John Wiley & Sons, New York, 1983)

[Rhoades & Ruffini(1974)] C. E. Rhoades and R. Ruffini, Phys. Rev. Lett., 32, 324 (1974)

[Lindblom(1984)] L. Lindblom, Astrophys. J., 278, 364 (1984)

[Witten(1984)] E. Witten, Phys. Rev. D, 30, 272 (1984)

[Farhi & Jaffe(1984)] E. Farhi and R. L. Jaffe, Phys. Rev. D, 30, 2379 (1984)

[Reynolds et al.(2007)] M. T. Reynolds, P. J. Callanan, A. S. Fruchter, M. A. P. Torres, M. E. Beer, and R. A. Gibbons, Mon. Not. R. Astron. Soc., 379, 1117 (2007)

[van Kerkwijk et al.(2011)van Kerkwijk, Breton, &x Kulkarni] M. H. van Kerkwijk, R. P. Breton, and S. R. Kulkarni, Astrophys. J., 728, 95 (2011)

Numerical relativity beyond astrophysics

Carsten Gundlach, University of Southampton c.j.gundlach-at-soton.ac.uk

A workshop on "Numerical relativity beyond astrophysics" was held at the International Centre for Mathematical Sciences (Edinburgh), 11-15 July 2011. (Here "beyond" is just funding body-speak for "not in".) The meeting was intended to refocus a bit on those applications of numerical relativity that are not motivated by astrophysical applications or the search for gravitational waves: critical collapse, higher dimensional gravity, AdS-CFT, etc. It was organised jointly by Carsten Gundlach, David Garfinkle and Luis Lehner. We tried to invite a mix of "numerical", "mathematical" and "strings" people, and focus each day on a particular topic, supplemented by a daily discussion session in the long lunchbreak.

Monday saw a good lineup of talks on **critical collapse**, with reviews of older work by *Gundlach*, *Oliver Rinne* and *Steve Liebling*. *Evgeny Sorkin* talked about his simulations of vacuum critical collapse in axisymmetry. He has not yet been able to repeat the results of Abrahams and Evans 1992, but claims to see a different kind of discrete self-similarity at the black hole threshold, with the maximum of the curvature on a ring. If this holds up, it would indicate discrete self-similarity in cylindrical symmetry (with the ring appearing straight at small scales).

The discussion session was a round-robin of introductions.

Tuesday was dedicated mainly to **black holes**. *Toby Wiseman* talked about methods for finding the zillions of black hole solutions in higher dimensions. If they are static, Wick rotation gives elliptic equations, which can be solved for example using Ricci flow. If they are only stationary, then more brute force methods are required. *Jorge Santos* talked about black holes with a single Killing vector field (in the first instance, in AdS5, with scalar hair). The KV has to be normal to the horizon to avoid rigidity theorems. *Lehner* reviewed recent work that settles the fate of the famous Gregory-Laflamme instability of a black string. Any almost-pinched off part of the string experiences a new GL instability, and so on, resulting in a naked singularity in finite time. *Fethi Ramazanoglu* talked about numerical simulations of black hole evaporation in 1+1 dimensions in the CGHS toy model of quantum gravity.

The discussion session was on critical collapse. It is very much still to be understood in axisymmetry!

Wednesday continued the black holes theme, with a review talk by *Mihalis Dafermos* on the effort to prove nonlinear stability. *Pat Brady* gave a review on black hole interiors: mass inflation for charged spherical black holes is now well understood, but Kerr is very much an open problem. The physical interpretation of the weak null singularity that precedes the usual spacelike one is also still unclear. *Masaru Shibata* showed impressive numerical evolutions of black holes in $D = 5, 6, 7$ dimensions (assuming $SO(D-3)$ symmetry). The Myers-Perry black hole is unstable above a critical spin, as expected. *Miguel Zilhao* and *Helvi Witek* gave a joint talk on recent simulations of BH collisions in higher dimension, again in $SO(D-3)$ symmetry. *Amos Ori* followed up Brady's talk with some speculation on what one expects to see in Kerr interiors and suggestions for numerical simulations. – The discussion session was on AdS-CFT. It began with an informal presentation by Wiseman, which led to very lively discussion.

Thursday was dedicated to **AdS-CFT**, but this strand had in effect begun on Tuesday afternoon with a lovely review talk for non-specialists by *Andrei Starinets*. *Piotr Bizon* presented strong numerical and analytical evidence for a nonlinear instability of AdS with

a minimally coupled scalar field (with Dirichlet boundary conditions). He explains it as resonance phenomenon in third-order perturbation theory made possible by the fact that the (linear) spherical scalar field modes have frequencies that differ by integers. This mechanism works in 3+1 and higher dimensions. It is slow, but much faster than the instability one might expect from Poincaré recurrence for a system in a box. *Jorma Louko* reviewed one key application of AdS-CFT, to the thermalisation of expanding plasmas (as a toy model for high-energy collisions of nuclei at RHIC). *Frans Pretorius* presented a general numerical method for evolving 5D asymptotically AdS spacetimes, using scalar matter fields and the generalised harmonic formulation. *Nick Evans* talked about probe branes as models of quarks at finite temperature, and *Harvey Reall* about horizon instabilities and local Penrose inequalities.

The extremely lively discussion session was a continuation of the previous one on AdS-CFT, this time kicked off by an informal presentation by Bob Wald querying the notion of causality in AdS-CFT. The way the string theorists think about the gravity side of AdS-CFT is certainly not the way relativists naturally think about an initial-boundary value problem for asymptotically AdS spacetimes! From gravity in the bulk one can read off a (conserved) stress-energy tensor on the boundary, which is supposed to be a quantum expectation value. But how does the quantum state in the boundary theory relate to classical initial data in the bulk?

A second discussion took place in the afternoon, on black hole interiors, kicked off by an informal presentation by Dafermos.

On Friday *Wald* discussed the bobbing and kicks seen in binary black hole mergers in terms of special relativistic toy models. These can be made rigorous in GR by introducing suitable center of mass world line and frame. *Lee Lindblom* presented a general method for solving PDEs on manifolds with arbitrary spatial topology. *Olivier Sarbach* reviewed the Cauchy problem for the Einstein equations on a finite domain, a topic pioneered by Friedrich for asymptotically AdS spacetimes before AdS-CFT became fashionable, and now relevant for numerical relativity. *Garfinkle* gave the last talk, on numerical simulations of the collapse of k-essence (a scalar field with nonstandard kinetic energy in the Lagrangian).

A hardy bunch met for tea and a last discussion session. The meeting had been rounded out by communal lunches at ICMS, two conference dinners, and even communal Scottish breakfast for those who felt like talking shop so early.

ICTP workshop on "Cold Materials, Hot Nuclei and Black Holes"

Vijay Balasubramanian, University of Pennsylvania vijay-at-physics.upenn.edu

Between the 15th and 26th of August this year, the ICTP, Trieste hosted a workshop focused on applications of the AdS/CFT correspondence to strongly coupled QCD and condensed matter systems. The workshop was organized by Vijay Balasubramanian, Jan de Boer, Veronika E. Hubeny, and Mukund Rangamani. There were two talks each morning and in the afternoon participants broke up into small groups discussing diverse topics. The discussions lasted through dinner, and then started again, often continuing past midnight on a patio facing the Adriatic Sea. It was just like a physics summer camp, complete with participants jumping into the nearby water to cool off.

The talks on applications to QCD focused primarily on the problem of thermalization and entropy generation. At RHIC, and more recently at the LHC, it has been shown that heavy ion collisions produce a complicated state of matter which thermalizes rapidly and produces a lot of entropy until it becomes a quark-gluon plasma which evolves hydrodynamically till the point where it hadronizes. Nuclear theorist Berndt Muller gave a talk discussing the extensive data that is becoming available, and presented the string theorists with various challenges (e.g. explaining the fluctuations in the energy emitted at different angular separations). Derek Teaney, also a nuclear theorist, explained how real-time methods from quantum field theory could be adapted to AdS/CFT to calculate properties of non-equilibrium configurations. Diana Vaman discussed new ways to perform real-time AdS/CFT computations and their applications to jet quenching, and Piljin Yi gave an overview of holographic approaches to studying baryons. Finally, Ben Craps described various holographic probes of thermalization and how they react in a model where energy is injected suddenly and then proceeds to equilibrate.

Several talks focused on the states of matter that are well approximated by fluid dynamics and their holographic description. Amos Yarom discussed holographic superfluids, Ramalingam Loganayagam discussed a holographic approach to the Wilsonian renormalization group that has a bearing on the fluid/gravity correspondence, and Cindy Keeler discussed the Harvard group's approach to getting a fluid dynamical description of gravity. A substantial number of speakers addressed the subtle issues in getting Fermi liquids and non-Fermi liquids in the AdS/CFT correspondence. Sandip Trivedi discussed how a variety of dilaton coupled gravities would give rise to different kinds of Fermi liquid behaviors. Shamit Kachru discussed instabilities of the AdS_2 space that typically appears in the near-horizon of the extremal black holes used to model cold materials, and explained how these instabilities will modify the deep infrared behavior of the dual field theory. Jerome Gauntlett discussed top-down constructions yielding interesting charged liquids and both Larus Thorlacius and Koenraad Schalm discussed how the back-reaction of fermions affects the AdS/CFT constructions of Fermi liquids.

Several talks addressed fundamental issues in the AdS/CFT correspondence that have a direct bearing on applications to condensed matter systems and QCD. Andrei Parnachev discussed conformal phase transitions at strong and weak coupling, and Simon Ross discussed the holographic description of asymptotically Lifshitz universes where space and time scale differently with the radius in spacetime. Micha Berkooz discussed the construction of D-brane configurations which could realize the sorts of intersecting defects that occur in many interesting condensed matter problems. Rob Myers gave a beautiful discussion of the Ryu-Takayanagi formula for holographic entanglement entropy and discussed approaches to

deriving this formula from first principles, at least in some special cases.

Two provocative talks, one in the first week, and one in the second, addressed foundational issues. The first, by the condensed matter theorist Sung-Sik Lee, proposed a novel characterization of gauge theories with gravity duals. The idea involved studying the dynamics of Wilson loops at certain critical points. Conference participants found this talk and the perspective it advanced very stimulating. The second talk, by Joan Simon, considered the problem of fast scrambling (the idea that black holes scramble information as fast as possible without violating any laws of physics). Joan discussed possible dynamical models that would give rise to this fundamental property which is implicated in all the studies that use AdS/CFT to study thermal behavior and thermalization.

The talks were uniformly of a very high quality. This was a very stimulating and successful meeting. In between discussions some people ate horse and wild boar. No one tried the spiced mountain goat. And no one was attacked viciously by sharks, bears, or even other participants.

Benasque Workshop on Gravity

Óscar J. C. Dias, DAMTP, University of Cambridge O.Dias-at-damtp.cam.ac.uk

Benasque is a charming little village in the heart of the Spanish Pyrenees, north of Barcelona. During 15 years, several scientific meetings took place in this village, mainly as the result of the effort undertaken by the Spanish physicist Pedro Pascual (1934-2006). As a recognition of his initiative, this Center for Science is now called "The Centro de Ciencias de Benasque Pedro Pascual". The Summer of 2009 signaled the opening of its new building, a modern facility designed as a place for work and interaction: plenty of desk space, omnipresent blackboards, common areas with coffee machines, and multifunctional conference rooms. This date and venue also marked the realization of the workshop "Gravity: New perspectives from strings and higher dimensions". Given the success of this experience (and as demanded by several of the participants!), the second edition of this workshop took place during July 17-29, 2011 (organized by Roberto Emparan, Veronika Hubeny and Mukund Rangamani) .

Over the last decade we have had remarkable progress in extending the field of application of General Relativity and in understanding various aspects of higher-dimensional gravity. Not only have we started to see many intriguing new solutions, but we are also witnessing the use of classical gravity as a tool being applied to plasma physics and condensed matter systems, and big advances in numerical relativity. More than fifty participants, gathered to discuss these developments, the current progress, and the future directions. The scheduled program for the workshop was light, with two hours of talks per day, plus a number of impromptu discussion sessions during some of the evenings (trust me: a lot of enthusiasm and action here!). There was time to enjoy the marvelous hiking in the surrounding mountains, and the local food. Some of the participants (and family) also extended their trip and visited Barcelona.

Mukund Rangamani opened the workshop with a discussion on the formulation of a holographic Wilsonian renormalization group flow for strongly coupled systems with a gravity dual. This provides an efficient extraction of low energy behavior of the system. The idea is to start with field theories defined on a cut-off surface in a bulk spacetime. Then, integrating out high energy modes in the field theory corresponds to integrating out a part of the bulk geometry. This formulation can be used to derive a semi-holographic description of low energy physics and provides an AdS/CFT interpretation of the membrane paradigm. (Work with Faulkner, Liu; Bratton, Camps, Loganayagam).

Roberto Emparan described the current state-of-the-art in what concerns the phase diagram of stationary, vacuum, asymptotically flat black holes in higher dimensional spacetimes. A full classification of these solutions is challenging, and he told us how the blackfold approach is a successful technique to identify important patterns in the phase diagram. This blackfold approach is an effective worldvolume theory for the dynamics of black branes. It allows for the perturbative construction of new black hole solutions. In addition, it is useful for the analysis of dynamical, non-stationary situations, like instabilities of black branes. (Work with Harmark, Niarchos, Obers; Caldarelli, Camps, Haddad, Rodriguez).

Jorge Santos presented the first examples of AdS black holes with scalar hair that are invariant under a single Killing field, which is the null generator of the horizon (so, they are neither stationary nor axisymmetric). They are related to rotating boson stars and to the endpoint of a superradiant instability. Moving to a related topic, Jorge reminded us that AdS spacetime with a scalar field is non-linearly unstable to transfering energy to smaller and smaller scales and eventually forming a small black hole. He then told us that a gravitational

turbulent instability is also present if we try to construct non-linear geons. The implications of this turbulent instability for the dual field theory, and the existence of single Killing field black hole counterparts of the geon were discussed. (Work with Dias, Horowitz).

Toby Wiseman reviewed the numerical framework for finding static and stationary vacuum black hole solutions in higher dimensions. He first explained the advantages of solving the Harmonic Einstein equation instead of the usual vacuum Einstein equation: the former is an explicit elliptic system. We can solve such a system using two relaxation methods, namely the Ricci flow (local relaxation) and Newton's methods. Toby then described two explicit solutions constructed using these elliptic numerical methods. One is the AdS_5 classical gravity dual of the CFT_4 on a Schwarzschild boundary background in the Unruh vacuum. The other is a large Randall Sundrum II static black hole. (Work with Headrick, Kitchen; Figueras, Lucietti).

Robert Myers gave a derivation of holographic entanglement entropy for spherical entangling surfaces. It relies on conformally mapping the boundary CFT to a hyperbolic geometry and observing that the vacuum state is mapped to a thermal state in the latter geometry. He also discussed holographic entanglement entropy with higher curvature gravity in the bulk. Here, Wald's formula for horizon entropy does not yield the correct entanglement entropy. However, for Lovelock gravity, Rob told us that there is an alternate prescription which involves only the intrinsic curvature of the bulk surface. (Work with Hung, Smolkin; Casini, Huerta).

Axions are scalars taking values in a circle; their periodicity prevents perturbative corrections to the potential; hence their mass is generated by nonperturbative effects. In confining gauge theories, one often finds the axion monodromy phenomenon: the energy is a multivalued functional of axion's angle, with a tower of metastable states above the ground state. The spectrum is periodic in shifts of the polar angle θ by 2π but the different states mix and reshuffe, and the energy grows with θ. Albion Lawrence discussed how axion monodromy can lead to interesting phenomena in cosmology and astrophysics, and how one can use it to build inflation models in field theory and string theory. (Work with Kaloper, Sorbo; Dubovsky, Roberts).

Donald Marolf discussed the encouraging ongoing efforts to find the AdS_5 classical gravity dual of the CFT_4 on a Schwarzschild boundary background in the Hartle-Hawking vacuum. This will be the AdS/CFT dual of Hawking radiation. More concretely, he described how the strong coupling behaviour of quantum field theories on a non-dynamical boundary black hole background can be described, in the context of the AdS/CFT correspondence, by a competition between two gravity duals: a black funnel and a black droplet. In this context, Don also told us about the possible existence of "flowing black funnels" that have a horizon rotating with different velocites as we move from the boundary into the bulk (these solutions have no Killing horizon so the rigidity theorem does not apply). (Work with Hubeny, Rangamani; Raamsdonk; Santos, Way; Fischetti).

Vitor Cardoso highlighted the window of opportunities that the gravitational wave detector experiments will provide for gravitational wave physics/astrophysics, for the strong-curvature regime of gravity, for black hole spectroscopy, and to test alternative theories of gravity. He reviewed the numerical evolution studies of the black hole binary/coalescence system: its three main phases (inspiral, merger and ring-down) and the technique used to extract the physical signal. Black hole collisions provide the most energetic phenomena in the universe, the best source of gravitational wave emission and they test the cosmic censorship and hoop conjectures. Several time evolution codes are now available and Vitor told us that we can

study high energy head-on and grazing collisions in four and higher dimensions. It is also possible to simulate zoom-whirl collisions where the black holes scatter after orbiting several times around each other, and collisions with kicks where the final black black is ejected with a large linear velocity.

In the last two years it was found that asymptotically flat, vacuum, black holes are unstable to the ultraspinning and bar-mode instabilities if they have large angular momenta. These results rely on numerical studies. Harvey Reall described how we can use simpler analytical methods to prove the existence of certain types of horizon instabilities. The idea is to find initial data that describes a small perturbation of the black hole and violates a local Penrose inequality. He told us how this approach confirms the existence of the Gregory-Laflamme instability on a black string and the existence of the ultraspinning instability. Moreover, it also proves that "fat" black rings are unstable. (Work with Figueras, Murata).

Stefano Giusto gave a detailed survey of the generating techniques that are being used to find extremal but non-BPS multi-center solutions, following their successful application to BPS systems. We need these solutions if we want to understand black holes within string theory and the microscopic origin of their Bekenstein-Hawking entropy. This program is particularly relevant to find if, and in what form, the so-called fuzzball proposal applies to BPS and non-BPS black holes. This proposal claims the existence of smooth horizonless configurations, with the same charges of the macroscopic black hole, that would be the microstates of the system and account for the statistical description of black hole thermodynamics. (Work with Bena, Bobev, Dall'Agata, Ruef, Warner).

Valeri Frolov considered four dimensional black holes embedded in models with large extra dimensions, and how events which are causally-disconnected along a lower dimensional hypersurface may be causally connected in the full spacetime. The idea is to study an induced geometry on a test brane in the background of a black string/brane. At the intersection surface of the test brane with the bulk black string/brane the induced metric has an event horizon; so the test brane contains a black hole dubbed a "brane hole". If the test brane moves with respect to the bulk, the emission and absorption of photons can be used to learn about the black hole interior. Indeed, from a test brane viewpoint such events are connected by a spacelike curve in the induced geometry. (Work with Mukohyama; Gorbonos). (During this workshop, Valeri also took the opportunity to promote his most recent book that includes a description of the more recent developments in black hole physics. The reader will certainly enjoy it!)

Witten diagrams are the tool for calculating correlation functions of strongly coupled conformal field theories with a gravity dual. In spite of significant progress, these calculations are however not easy and only a small number of explicit computations have been done. Traditionally, these are performed either in coordinate or in momentum spaces. Miguel Paulos proposed changing basis. He told us what are the benefits of working with the embedding formalism and the Mellin transform. This allows the calculation of certain tree-level conformal correlation functions in AdS/CFT that were not computed using the standard Fourier transform.

Take the QCD phase diagram of temperature T versus chemical potential μ for baryon number. There are computational tools available to study this system in two regions, namely the large T (QGP) regime and the large μ (CFL) phase. In between, there is a strongly coupled region that should be described by strongly interacting deconfined quarks. Unfortunately, the Lattice QCD simulations are not a useful tool to explore it. Prem Kumar proposed using a dual holographic gravity description of the system to get insights about

the fundamental properties of this system. The idea is to use D-brane systems that have a confinement/deconfinement phase transition, and a phase diagram that shares important common features with QCD, to learn about strongly coupled quark dense matter. This program is being implemented in the D3/D7 brane system and associated Hedgehog black hole. (Work with Benicasa).

During the workshop, there were enthusiastic discussions and intense interactions. The overall open and collaborative atmosphere was very much appreciated by everyone. It was generally felt that such a successful and enjoyable meeting should have a continuation, and plans to hold a third Benasque Workshop on Gravity in July 2013 are already underway.